AFGL-TR-86-0203

PRELIMINARY INVESTIGATION OF IONOSPHERIC MODIFICATION
USING OBLIQUE INCIDENCE HIGH POWER HF RADIO WAVES

Gary S. Sales
Bodo W. Reinisch
Claude G. Dozois

AD-A179 174

University of Lowell
Center for Atmospheric Research
450 Aiken Street
Lowell, Massachusetts   01854

September 1986

Scientific Report No. 6

DTIC
ELECTE
APR 2 0 1987
E

"This technical report has been reviewed and is approved for publication"

JACKIE B. WAARAMAA
Contract Manager
Ionospheric Effects Branch

HERBERT C. CARLSON, Chief
Ionospheric Effects Branch
Ionospheric Physics Division

FOR THE COMMANDER

ROBERT A. SKRIVANEK
Director
Ionospheric Physics Division

This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain additional copies from the Defense Technical Information Center. All others should apply to the National Techncial Information Service.

If your address has changed, or if you wish to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify AFGL/DAA, Hanscom AFB, MA 01731. This will assist us in maintaining a current mailing list.

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-86-0203	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PRELIMINARY INVESTIGATION OF IONOSPHERIC MODIFICATION USING OBLIQUE INCIDENCE HIGH POWER HF RADIO WAVES		5. TYPE OF REPORT & PERIOD COVERED Scientific Report No. 6
		6. PERFORMING ORG. REPORT NUMBER ULRF-435/CAR
7. AUTHOR(s) Gary S. Sales Bodo W. Reinisch Claude G. Dozois		8. CONTRACT OR GRANT NUMBER(s) F19628-83-C-0092
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Lowell, Center for Atmospheric Research, 450 Aiken Street, Lowell, Massachusetts 01854		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62101F 464308AD
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory Hanscom AFB, Massachusetts 01731 Contract Monitor: J. B. Waaramaa/LIS		12. REPORT DATE September 1986
		13. NUMBER OF PAGES 44
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Ionosphere
Modification
High Frequency (HF)
Propagation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A special experiment was carried out using a high powered transmitter and a high gain rhombic antenna to heat the ionosphere at a distance of 1300 km from the transmitter. A Digisonde ionospheric sounder was located at the midpoint to sense any changes that might occur in the ionosphere at the heating cycle period of ten minutes. The measured phase data was processed using spectrum analysis in an attempt to detect this ten minute period.

DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE
1 JAN 73

20. ABSTRACT (Continued)

The results are not conclusive but there is some indication that the heating period was detected only during the nighttime in agreement with theoretical prediction. Key words: → to field 19

TABLE OF CONTENTS

Accession For

NTIS GRA&I	☑	
DTIC TAB	☐	
Unannounced	☐	
Justification		

By
Distribution/

Availability Codes

Dist	Avail and/or Special
A-1	

QUALITY INSPECTED 2

iii

LIST OF FIGURES

1.0 INTRODUCTION

Using the published experimental results of G. S. Bochkarev, et al. (1982), it was decided to attempt to reproduce their work using a high powered transmitter located in Ava, New York. Because significant detail is omitted in the Bochkarev paper it was necessary to design the experiment using, in addition, the theoretical work published by Gurevich (1978) and other work along the same lines by Field and Warber (1985a). Bochkarev described an experiment, initially performed in 1974, using a high-powered HF transmitter to obliquely "heat" the ionosphere some 900 km down range, altering the ambient electron density structure and producing a significant change in a "wanted" radio signal propagating through the disturbed region.

This technology, in addition to perturbing a wanted radio wave passing through a disturbed region, can be used to describe how other high-power HF radio systems such as an over-the-horizon radar or a broadcast system, such as Voice of America, could affect their own signal by the same modification process.

2.0 THEORY

Under consideration here is the effect of high-power radio waves on the ionosphere. At "normal" power levels used by most communication or sounding systems, it is only necessary to consider the effect of the ionosphere on the radio wave. With the more powerful transmitters now in use, the inverse effect must also be investigated.

With application to this current program, a complete review of previous experiments and theory has been presented by Field and Warber (1985b). Only the important points necessary for the design of this experiment will be presented here. Heating caused by the interaction of the intense electric field, produced by the HF disturbing wave, with the plasma is considered. Field has shown that the most intense electric fields occur in the caustic region formed near the reflection point in the F-region of the ionosphere. In this respect, this process is the same as for vertical incidence heating where strong E fields are generated just below the $X - 1$ level in the ionospheric plasma (Shoucri, 1986).

The structure of the caustic region is described in Figures 5 through 9 in Field's report. (Figures 5-9, 10 and 12 from the Field report are presented in the appendix to this report.) With the disturbing transmitter described in the Field paper, i.e. $P_T - 100$ kW, $G_T - 20$ dB and a range of approximately 1,300 km to the reflection point, electric fields were predicted, for the nighttime, with intensities in the range of 0.2 to 0.4 (Vm^{-1}) over a small region approximately 200 km in range at an altitude of 260 to 290 km. The exact location, in range, of the caustic region depends on the ratio of fop/foF2, where fop is the disturbing transmit-

2

ter operating frequency and foF2 is the maximum plasma frequency of the F-layer of the ionosphere. For fixed ionospheric conditions the region of intense E field can be moved to shorter or longer ranges by changing the operating frequency. In daytime the predicted field strength varies from 0.1 to 0.2 (Vm^{-1}) over the same sized region at a somewhat lower altitude (240 to 260 km). The disturbed altitude depends on the particular background ionospheric model chosen. Although models such as IONCAP are useful in planning such an experiment, a better real-time method had to be developed for use in the field to determine the location of the heated region.

The theory presented by Field and Warber indicated that there was no reason to expect an abrupt onset of heating in terms of disturbing transmitter power and that there was a relatively simple relationship between transmitter power and the magnitude of the heating effect. Finally Field calculated the expected time constants for heating and cooling of the plasma (cooling occurs when the disturbing transmitter is turned off). Heat conduction and thermal diffusion are not considered in the preliminary work by Field.

Figure 10 in Field's report indicates the heating and cooling variations parametrically in E/Ep as a function of a characteristic time t_0. Both Ep and t_0 were defined originally by Gurevich. For this experiment, Ep $\approx$ 0.3 V/m and t_0 $\approx$ 20 seconds are the appropriate values. Using Figure 10 (Field), the heating cycle should then be at least 120 seconds on and 120 seconds off. This will produce a temperature change of 0.2 to 0.4 times the ambient temperature.

At the time of the planning of this experiment the associated change in electron density (N) was not available and it was assumed that the change in N would follow the change in temperature. In fact, recent work by Shoucri indi-

3

cates that the electron density variation caused by the heating produces a depleted electron region that recovers more slowly than the temperature. This results from the fact that the more massive ions diffuse relatively slowly back into the heated "void." The electrons are constrained to follow these slow moving ions. The different time constants associated with ΔT and ΔN will have an impact on the outcome of the experiment.

3.0   EXPERIMENTAL PLAN

Although the Soviet authors used an oblique "wanted" wave to indicate the presence of the disturbed ionosphere, it was decided that a better measurement, one that would provide quantitative data concerning the structure of the disturbed region, would be preferable. With limited resources, it was decided to establish only a midpoint site and make direct measurements from below the heated region rather than using a down range site as did Bochkarev.

The next problem addressed was the type of measurement that should be made that would be sufficiently sensitive to detect an effect which was expected, on the basis of the theoretical analysis, to be relatively small. Unfortunately the published work of Bochkarev never discussed his transmitter powers or antenna gains, data that would have been useful in planning this experiment. Expecting small changes it was decided that a phase measurement would be the most responsive. It was decided to install an ULCAR Digisonde 256 which would provide both vertical incidence ionograms and fixed-frequency phase measurements. The vertical incidence ionograms describe the gross ionosphere at the midpath and provide the disturbing transmitter at Ava, New York with frequency management information. The Digisonde's ARTIST (Reinisch and Huang, 1983) automatically scaled the ionograms and calculated the MUF(2600), which was telephoned to the transmitter site at Ava.

Before discussing in detail the phase measurements at the midpoint site, a brief description of the transmit site is necessary. The USAF Rome Air Development Center facility at Ava, New York (43° 30'N, 75° 20'W) is the site where a high power (up to 300 kW) CW transmitter and a hori-

5

zontal rhombic antenna is located. The horizontal rhombic, bore-sighted at a bearing of 230° T, provided a useful path over the southern United States. The choice of midpath site was based on several criteria. The selected site had to lie along the antenna bore-sight, the range to this site should be between 1,000 and 1,500 km from Ava, New York and, finally, the site should provide support and security for the equipment. On this basis the choice was made for the Arnold AFS at Tullahoma, Tennessee (35° 20'N, 86° 20'W). The distance between the transmitter and midpoint site is approximately 1,300 km. The total path back to the ground is then 2,600 km, a reasonable one hop F-layer path. Figure 1 shows a map of the area indicating the two sites.

The overall experimental configuration is shown in Figure 2 with the Digisonde 256 ionospheric sounding system located at Tullahoma, Tennessee near the midpoint of the path. As seen in Figure 2 and Figures 5 through 9 in Field's report, the caustic region lies at the "long" range side of the midpoint and for that reason the disturbing transmitter frequency must be adjusted appropriately so that the heated region lies over the sounding site.

Beyond the determination of the midpoint sounding site, two other critical factors had to be addressed before ⁺he experiment could begin. These problems are the heating cycle period and effective frequency management techniques.

It was decided to use a ten-minute heating cycle, that is the disturbing transmitter was on for five minutes and then off for five minutes. For the relatively low field strengths, using Figure 10 of Field's report, equilibrium can be reached within five minutes. The recovery back to ambient temperature is also shown to be complete within five minutes.
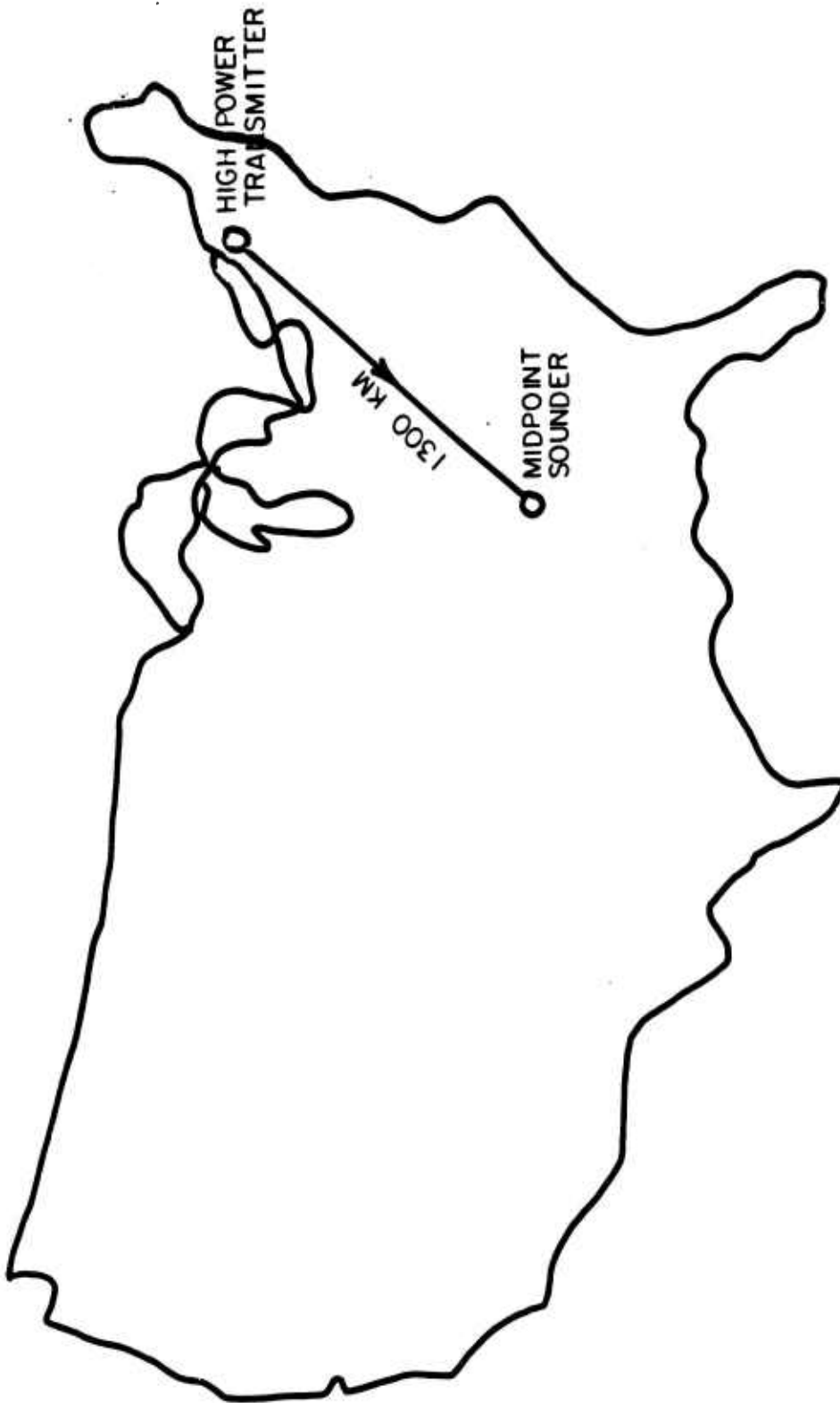
6

Figure 1. Experimental configuration: Transmitter in Ava, NY to the midpoint Digisonde at Tullahoma, TN

STRONG NON-LINEAR
IONOSPHERIC INTERACTION

F-LAYER
IONOSPHERE

CAUSTIC
REGION

DISTURBING HF
TRANSMITTER

VERTICAL IONOSONDE
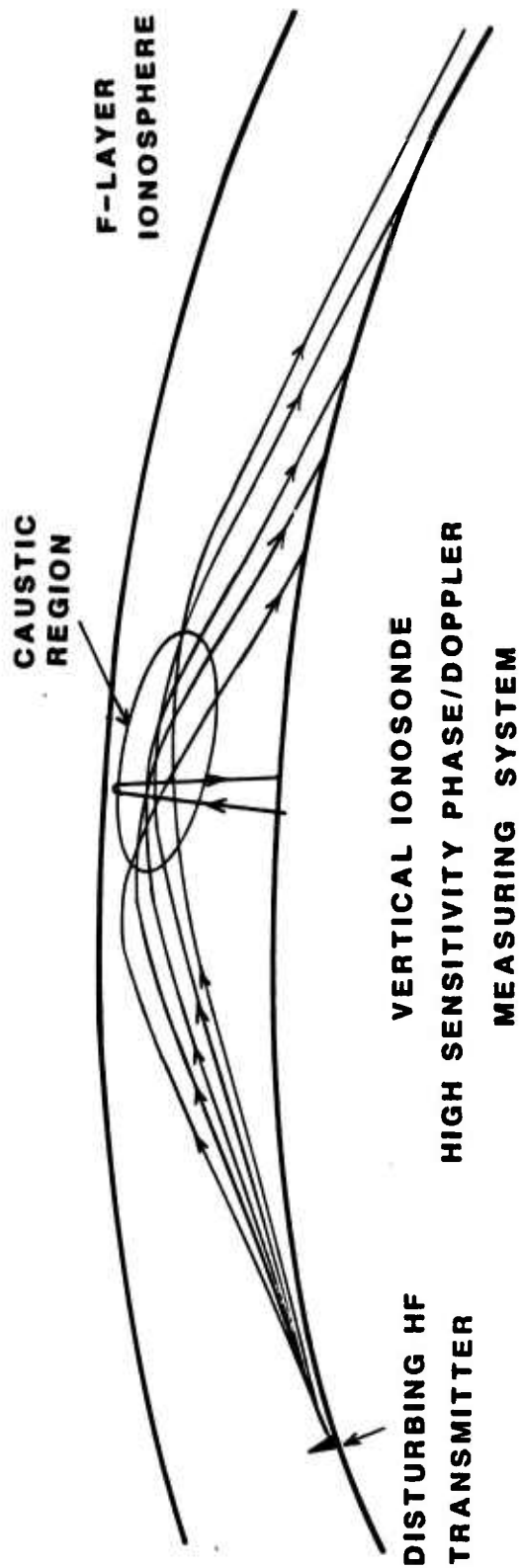HIGH SENSITIVITY PHASE/DOPPLER
MEASURING SYSTEM

Figure 2.   Pictorial description of ray paths showing the location of the
caustic region

8

Before addressing frequency management it was recognized that it might not be apparent when the caustic region would be over Tullahoma and it was decided to insure that at some time the heated region was located properly, the disturbing frequency was to be varied, in the process moving this region in and out over Tullahoma. Since the modified region has a range dimension of approximately 100 km, it required a frequency change of ±500 kHz in the daytime and ±250 kHz at night to move the heated region ±100 km. These frequency changes would be made on sequential heating cycles so that over a period of thirty minutes the caustic region would, with a high probability, fall over Tullahoma.

The other problem was to develop a method for determining the best frequency to be used for heating on a thirty-minute basis. Two techniques were employed to try to insure that the modified ionosphere was in the proper location. First, the vertical incidence sounding at Tullahoma was scaled for the MUF(2600), and this data was telephonically relayed to the Ava transmit site. The second method used the wideband ground backscatter ionogram made at Ava with a relatively low power (5 kW) transmitter and a horizontal log periodic antenna looking in the same direction as the disturbing transmitter. These backscatter ionograms were scaled for the maximum usable frequency for a range of 2,600 km. The frequency determined by the two methods was compared and an operating frequency was determined.

The experiment began on 15 May 1984 (J. D. 136) and ended on 24 May 1984 (J. D. 145). Although the Digisonde site at Tullahoma ran continuously during this period, limited manning at the Ava site permitted only eight-hour operations per day and not on the weekends. Figure 3 shows the measured variation of foF2 for the period of the experiment. The time scale is Central Standard Time (CST), corresponding
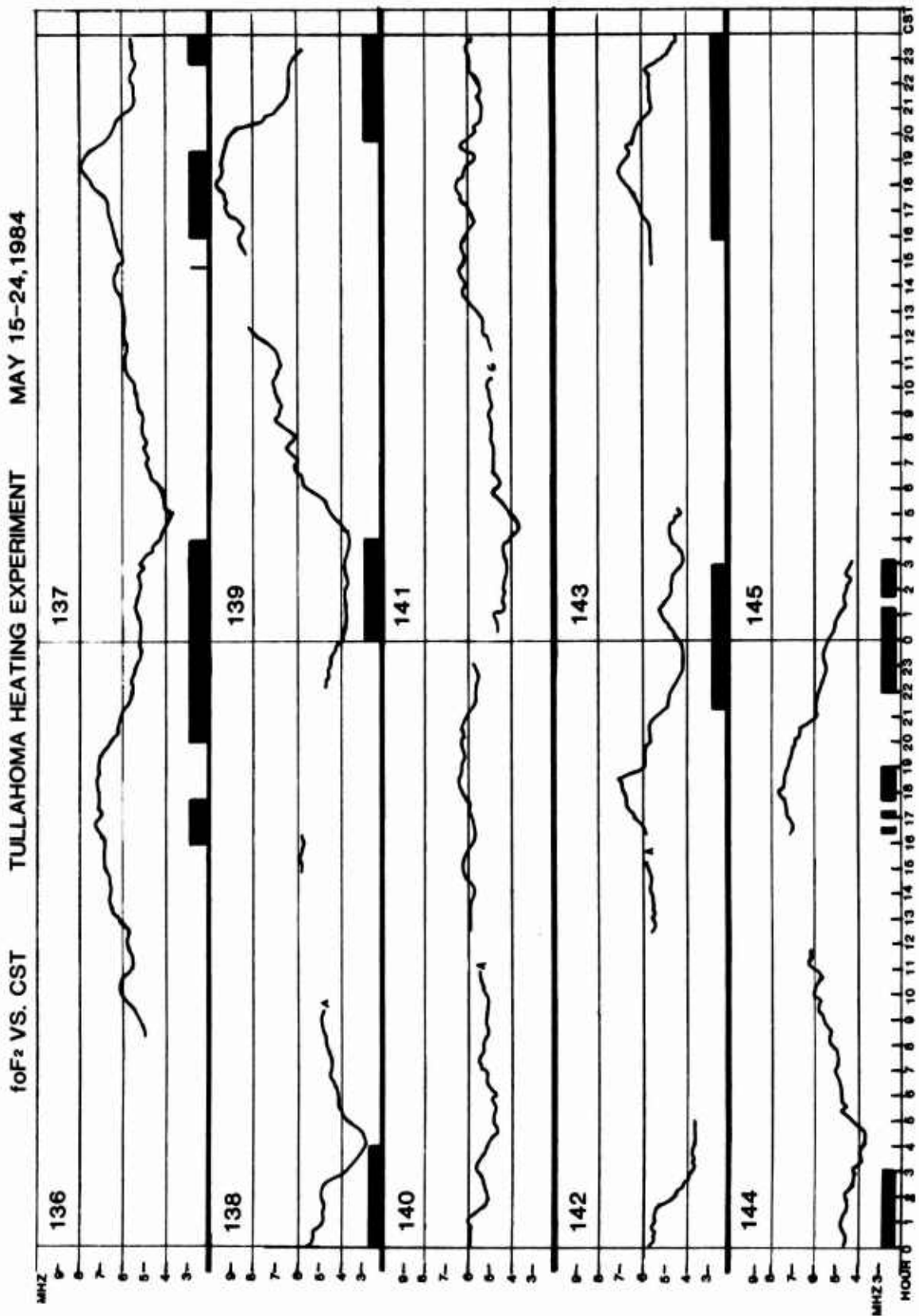
Figure 3. Diurnal variation of foF2 at Tullahoma, TN for the ten day experiment

to Tullahoma, Tennessee, and the gaps in foF2 were usually caused by blanketing sporadic E. The solid bars at the bottom of most days indicate the periods when the Ava disturbing transmitter was operating. It is apparent that most of the operations were during the nighttime period from 1900 CST through 0500 CST. This was based on Field's analysis indicating a stronger effect at night. No heating experiments were carried out on days 140 and 141 as these were a Saturday and Sunday. As will be discussed later, the data analyzed for this report was concentrated in days 143, 144 and 145 producing a total twenty-four hours of phase data. This period was carefully analyzed because the disturbing transmitter power was increased late in the experiment from 100 kW to 200 kW in an attempt to increase the probability of success.

The ten-minute heating cycle was divided into five 96-second time intervals for the phase measurements. Figure 4 describes the relationship between the heating cycle and the phase measurement cycle. The second phase measuring cycle which would have begun at 2 minutes and 20 seconds into the heating cycle was replaced by a vertical incidence ionogram. In retrospect, making a vertical incidence ionogram every ten minutes and in the process disrupting the periodic phase measurements (two minute samples) may have reduced the signal-to-noise ratio of the processed phase variations. Once every thirty minutes for the VI ionograms would have been sufficient.

The fixed frequency phase measurements were made using the equivalent vertical frequency corresponding to the same virtual height as the oblique disturbing transmissions.
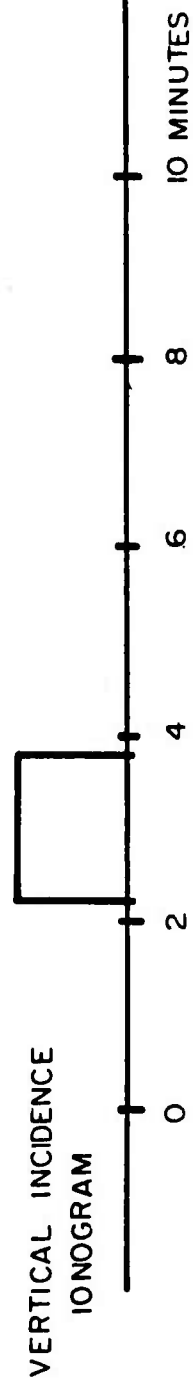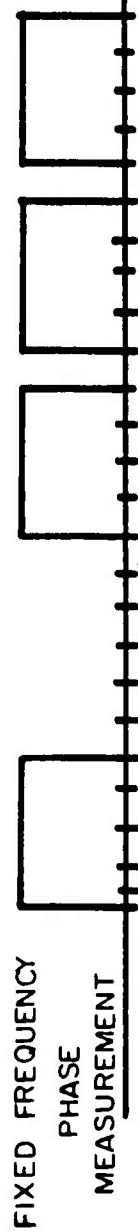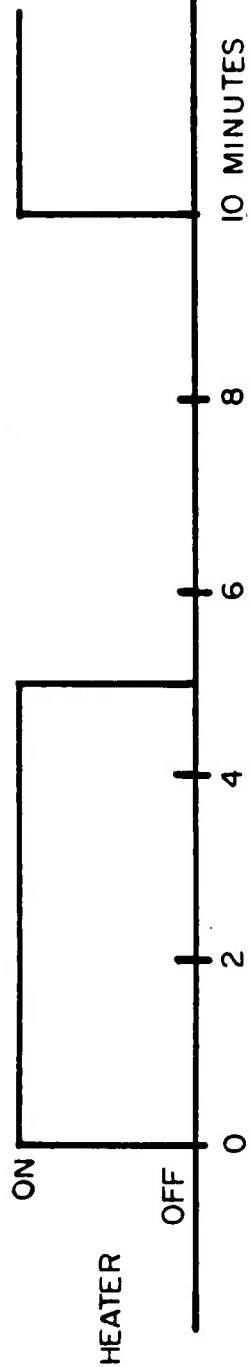
Figure 4. Relationship between heating cycle and the Digisonde phase measurements

HEATER

ON

OFF

FIXED FREQUENCY
PHASE
MEASUREMENT

VERTICAL INCIDENCE
IONOGRAM

10 MINUTES

12

4.0 DATA PROCESSING

The vertical ionograms were routinely scaled for the entire period and the ten-minute foF2 values are presented in Figure 3.

The basic concept for processing the phase data was to detect the modulation period imposed by the on/off cycling of the disturbing transmitter. The period of the fundamental frequency in this case was expected to be ten minutes.

To model the effect of the disturbing transmitter it was assumed that the phase changes closely followed the temperature changes. The expected temperature change with time is shown in the Field report, Figure 12 (see Appendix A) for realistic values of E/Ep - 0.6 and t_0 - 20 seconds. To the extent that the phase variation followed this temperature change, a ten-minute fundamental period should be introduced into the phase data.

With what appeared to be relatively noisy phase data it was decided to average the phase change over a period of ninety-six seconds (128 points spaced 0.75 seconds apart). This close spacing of 0.75 seconds was selected to insure that this averaging over ninety-six seconds does not miss any 2π rotations between successive points. One example of these phase difference measurements is shown in Figure 5. The six overlaid curves correspond to the start times for the six heating cycles within one hour. These six data samples represent the same epoch relative to the heating cycle; in this case they start within the first minutes after the disturbing transmitter is turned on. The ordinate, the average Doppler frequency, is the measured change in phase within 96 sec divided by $2\pi T$ where T - 96 seconds.

GRAPH SYMBOL:	NONE	+	×	◆	◎	▣
NOMINAL START TIME:	0′57″	10′57″	20′57″	30′57″	40′57″	50′57″
ACTUAL START TIME:	0′37″	10′37″	20′37″	30′37″	40′37″	50′37″
DELTA-PHI MAX (DEG):	-93	-50	38	-23	34	71
DELTA-PHI AVE (DEG):	9	-43	-74	-150	-115	-31
DELTA-PHI SIG (DEG):	22	21	13	13	16	30
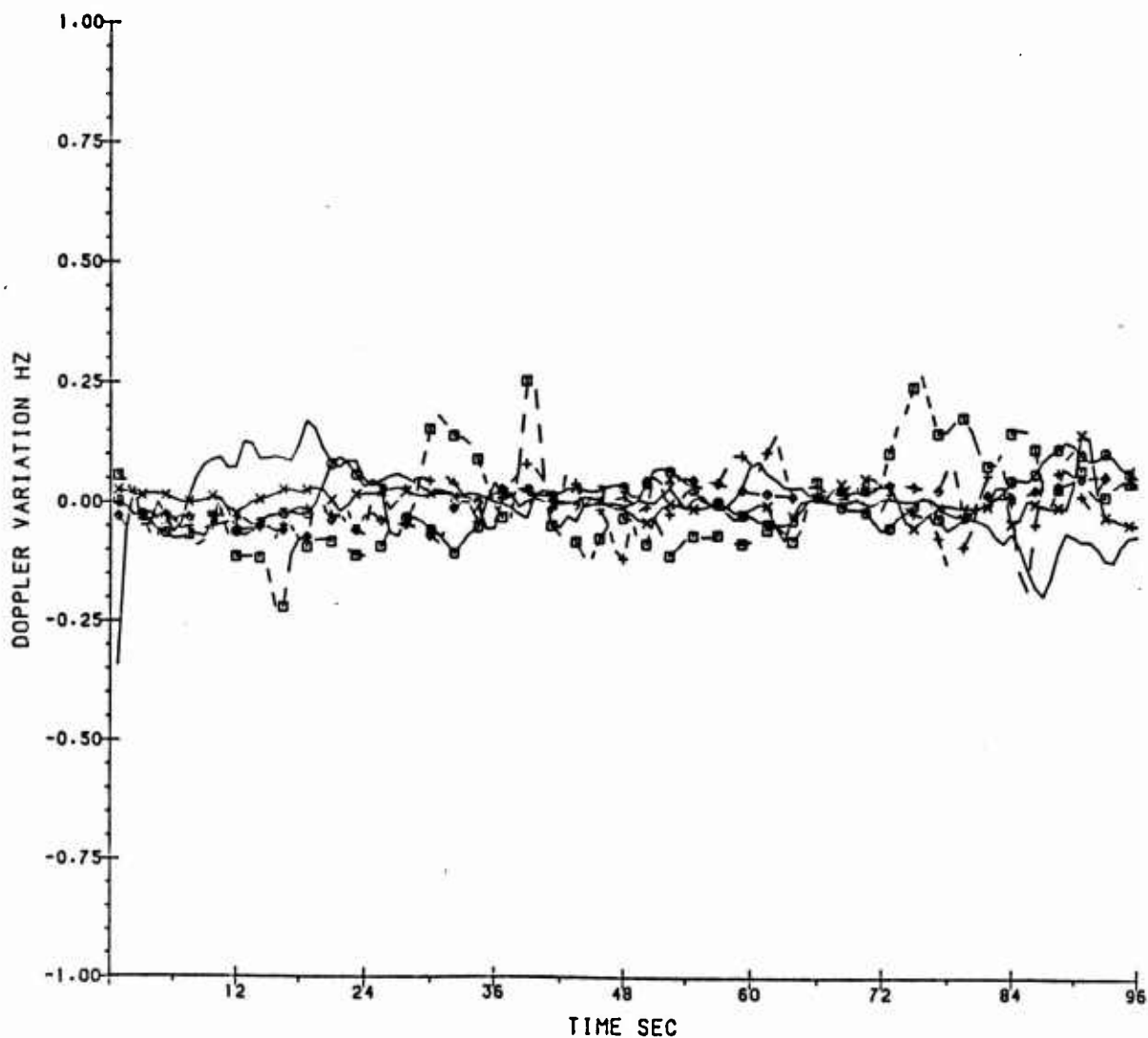
Figure 5. Phase variation data: superposition of six heating cycles (one hour)

The relatively constant values represent an unchanging Doppler shift, in this case, very close to zero. The averaging process is formed by using the expression:

$$\Delta\phi_j = \sum_{i=1}^{128} \Delta\phi_{ij}$$

This averaging process produces a mean phase change over the 96-second period with little likelihood of missing any 2π rotations. The "j" index represents the thirty values in one hour of heating (five averaged periods spaced two minutes apart per ten-minute cycle). For the particular date and time indicated in Figure 5 (J. D. 144, 22 UT), the variation of the $\Delta\phi_j$ is shown in Figure 6. The ordinate represents the mean phase change in degrees. As shown in Figure 4, one two-minute sample out of each six is omitted so that a vertical incidence ionogram could be made. In all cases, except at the beginning of this hour, the missing point was filled in by interpolation and are indicated by the circled points.

In these data (Figure 6), the procedure is to find a ten-minute component corresponding to the heating cycle indicated at the bottom of the figure. Typically there are large scale slow fluctuations superimposed on any ten-minute period that may be present. These long period cycles are possibly produced by a travelling ionospheric disturbance (TID) passing over the site. A discrete Fourier transform was applied to the $\Delta\phi_j$ data in an attempt to detect the ten-minute period. These data were first detrended (linear variation removed) to remove the very lowest frequency components including the mean from the data.

As stated earlier, this processing was applied to the last three days of the experiment when the disturbing
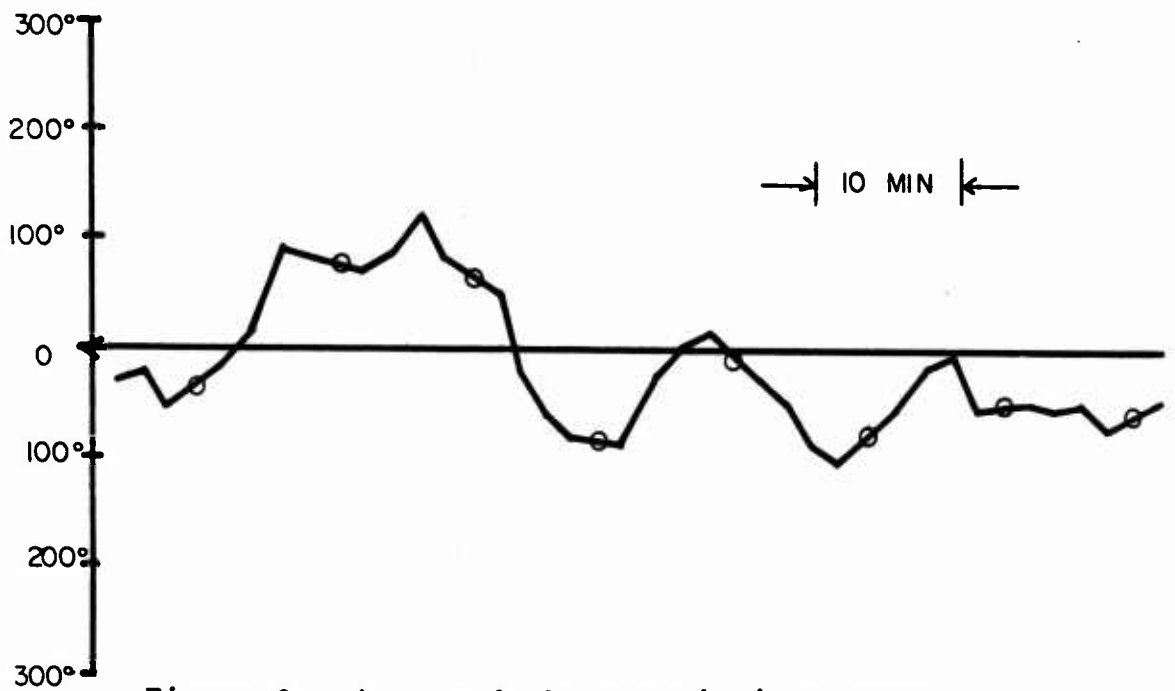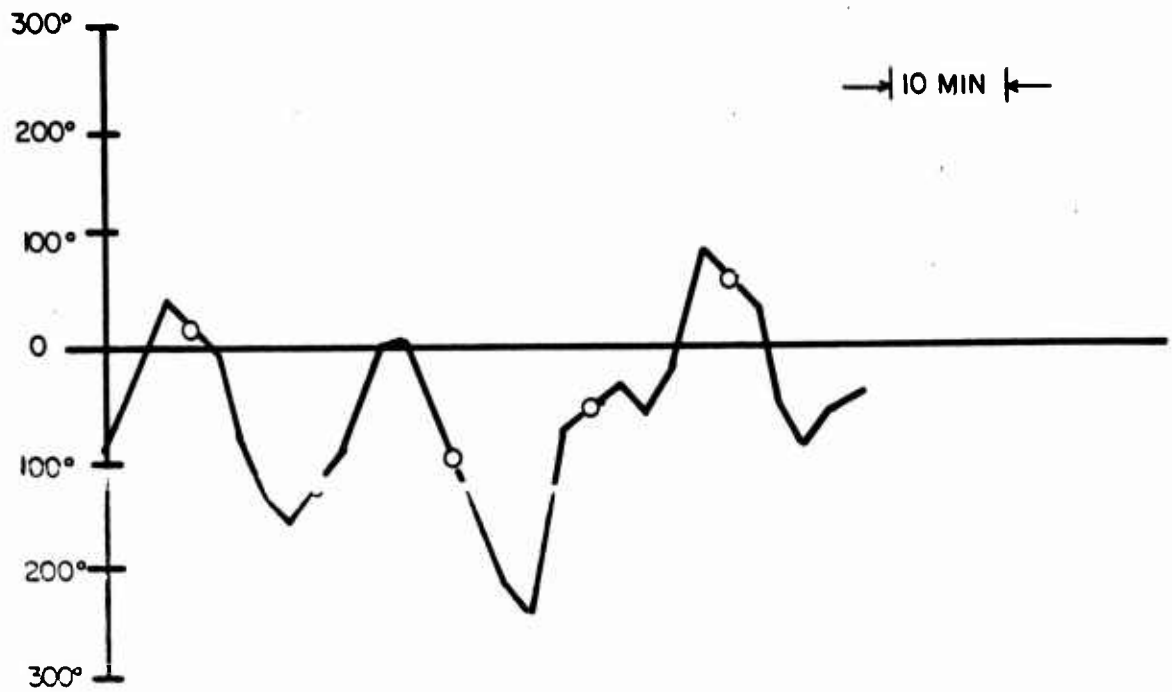
Figure 6. Averaged phase variations over
a one hour period

16

transmitter power was run at 200 kW. The results of the
spectral analysis is discussed in Section 5.0.

5.0 ANALYSIS

Over the three-day period in May 1984, some twenty-four intervals of data, each approximately one hour long, were processed for this analysis. These three days were selected, as stated earlier, because the disturbing transmitter was operated at the highest output power, i.e., 200 kW.

These data were divided into two time intervals, both to increase the sample size and to determine whether any diurnal trends could be detected.

Day: (1200 CST to 2000 CST) - 8 samples

Night: (2000 CST to 0400 CST) - 16 samples

Typical spectra for day and night are shown in Figure 7. Here the large amount of power contained in the slow fluctuations (see Figure 6), i.e. T > 10 minutes, is the dominant feature of these spectra. All of these hourly data were superimposed and a median spectrum determined for the day and night period, separately. These results are shown in Figure 8. These data again indicate a large amount of natural fluctuations at long periods. It is against this background of natural phase variations, very likely caused by passing acoustic gravity waves, that the experimental ten-minute modulation must be detected. Under the most optimistic expectations, a clear peak at the ten-minute period and a secondary peak at five minutes could be expected.

Recognizing the dominant role played by the long period natural waves in the median day and night spectra, a simulation of the observed spectra is attempted so as to isolate component waves which are likely outside the naturally occurring spectral distribution associated with these acoustic gravity waves. Of particular interest is the amplitude
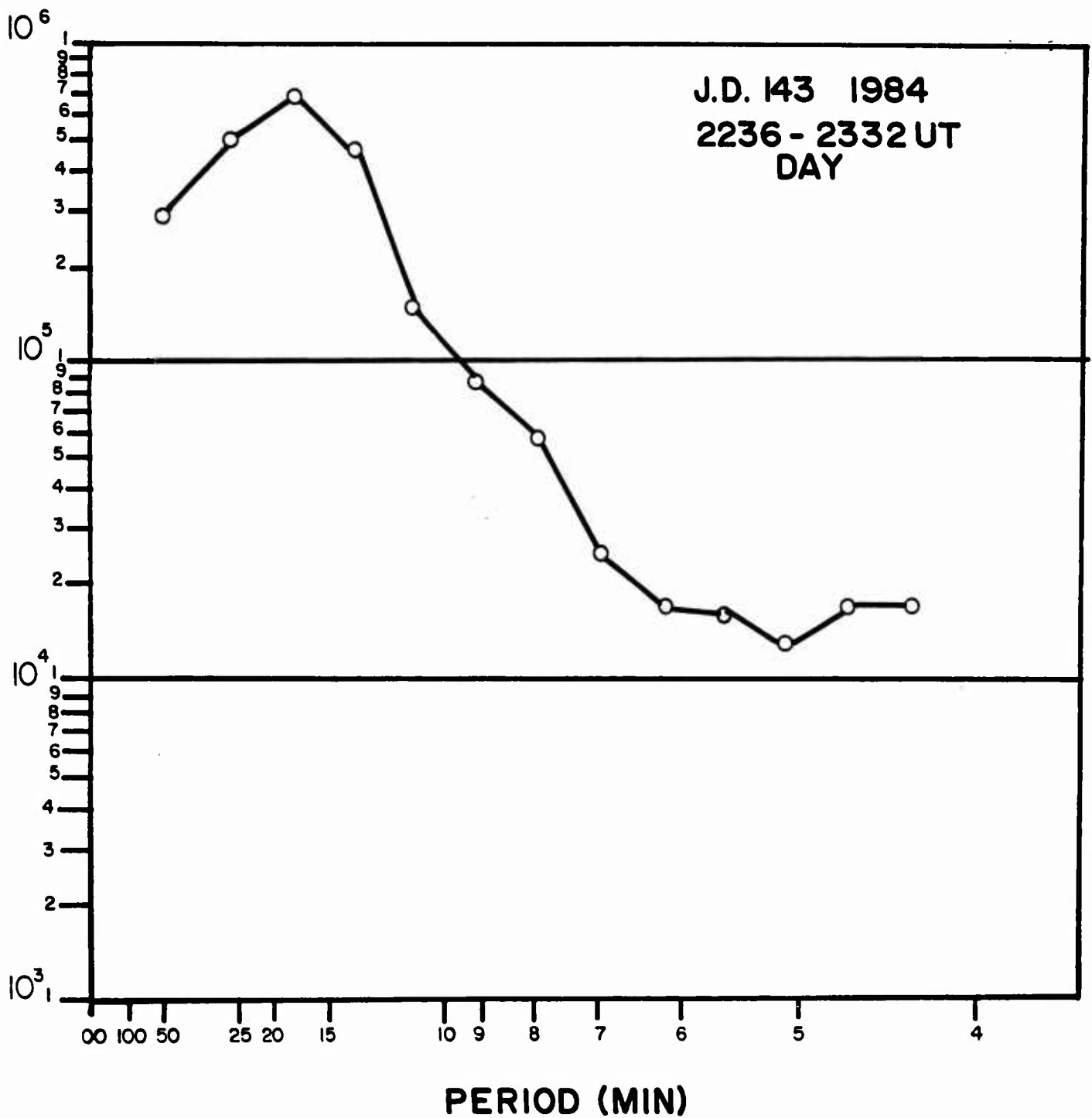
18

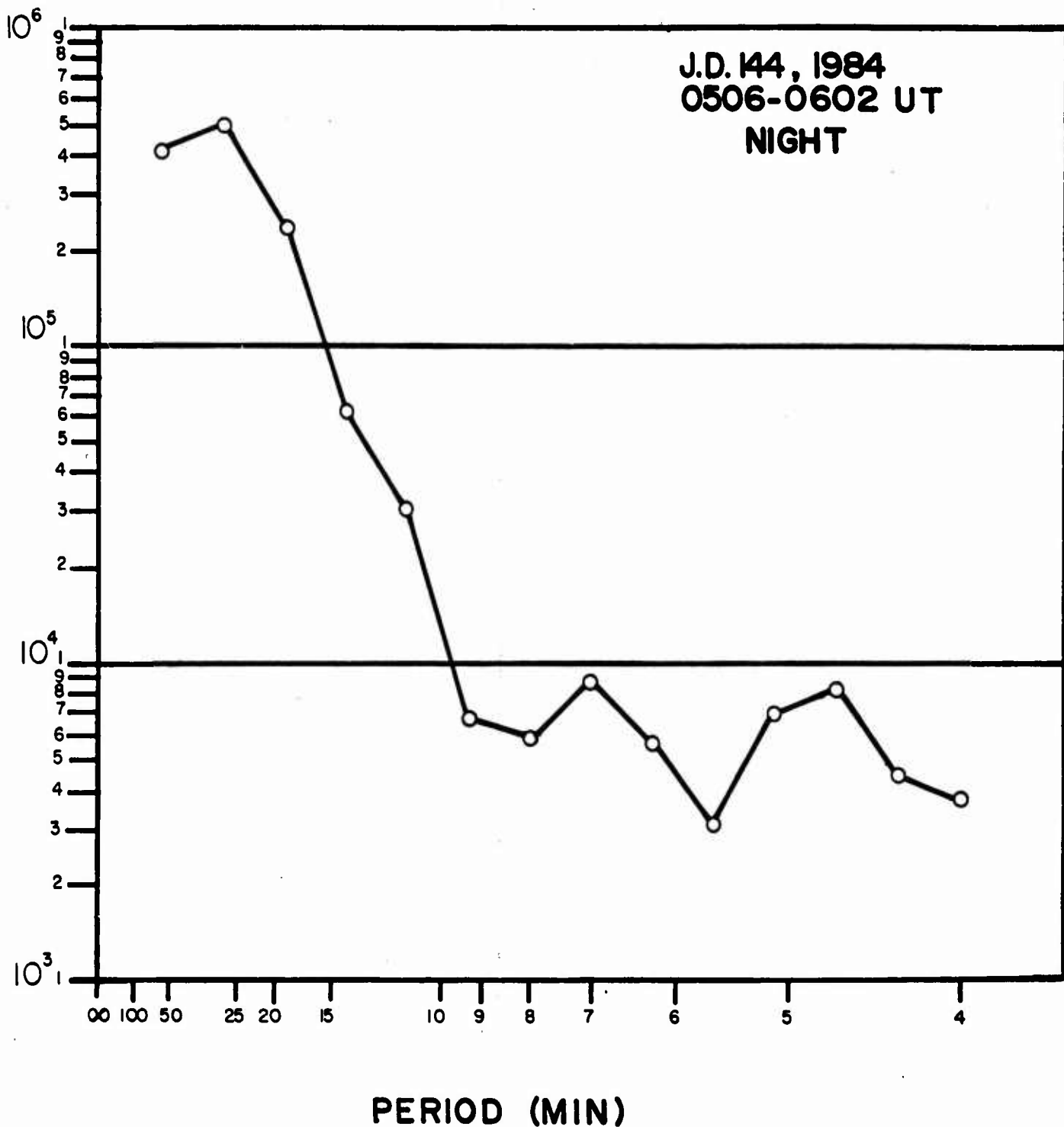Figure 7a. Typical spectrum of phase variation - daytime

19

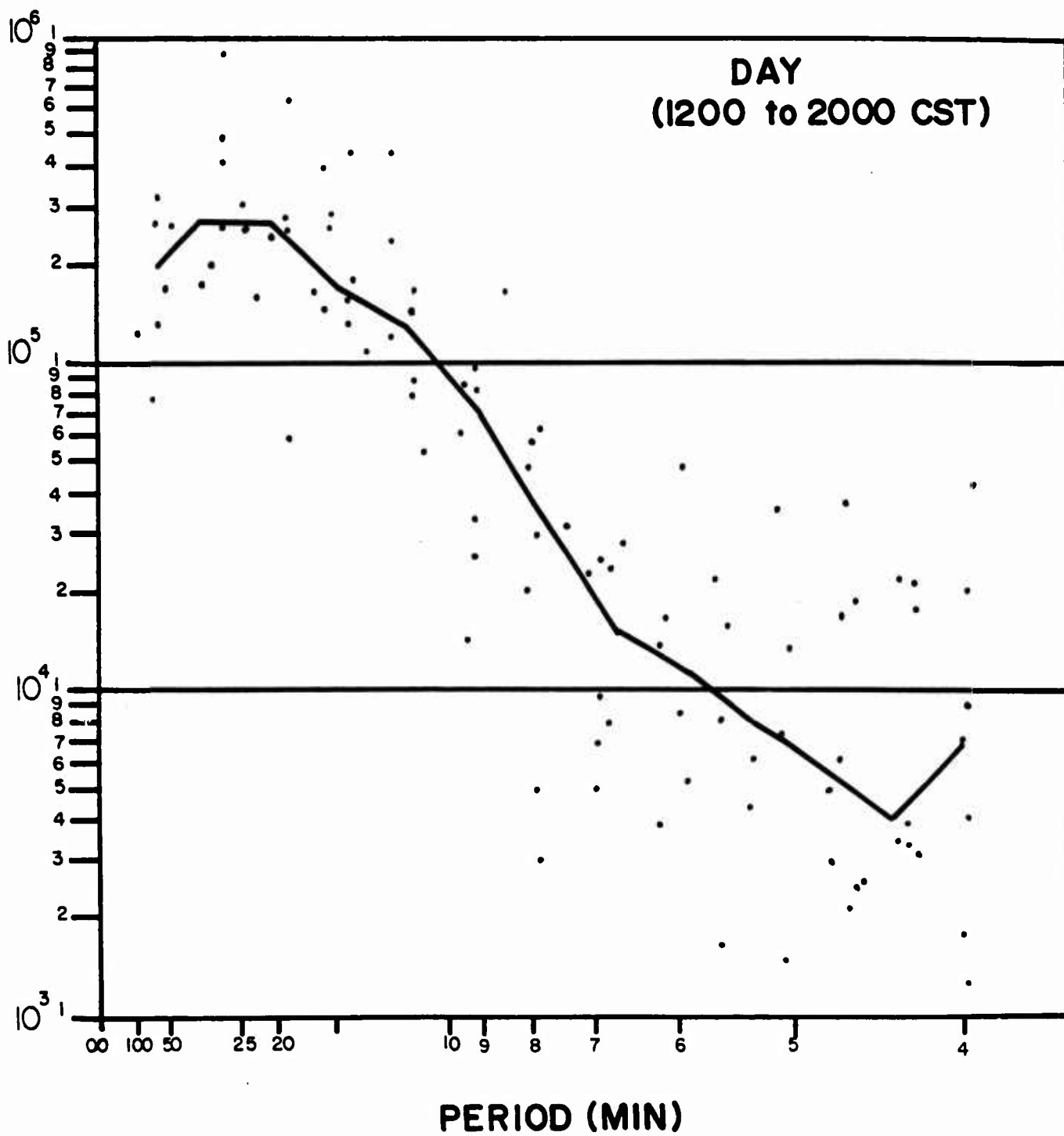Figure 7b. Typical spectrum of phase variation - nighttime

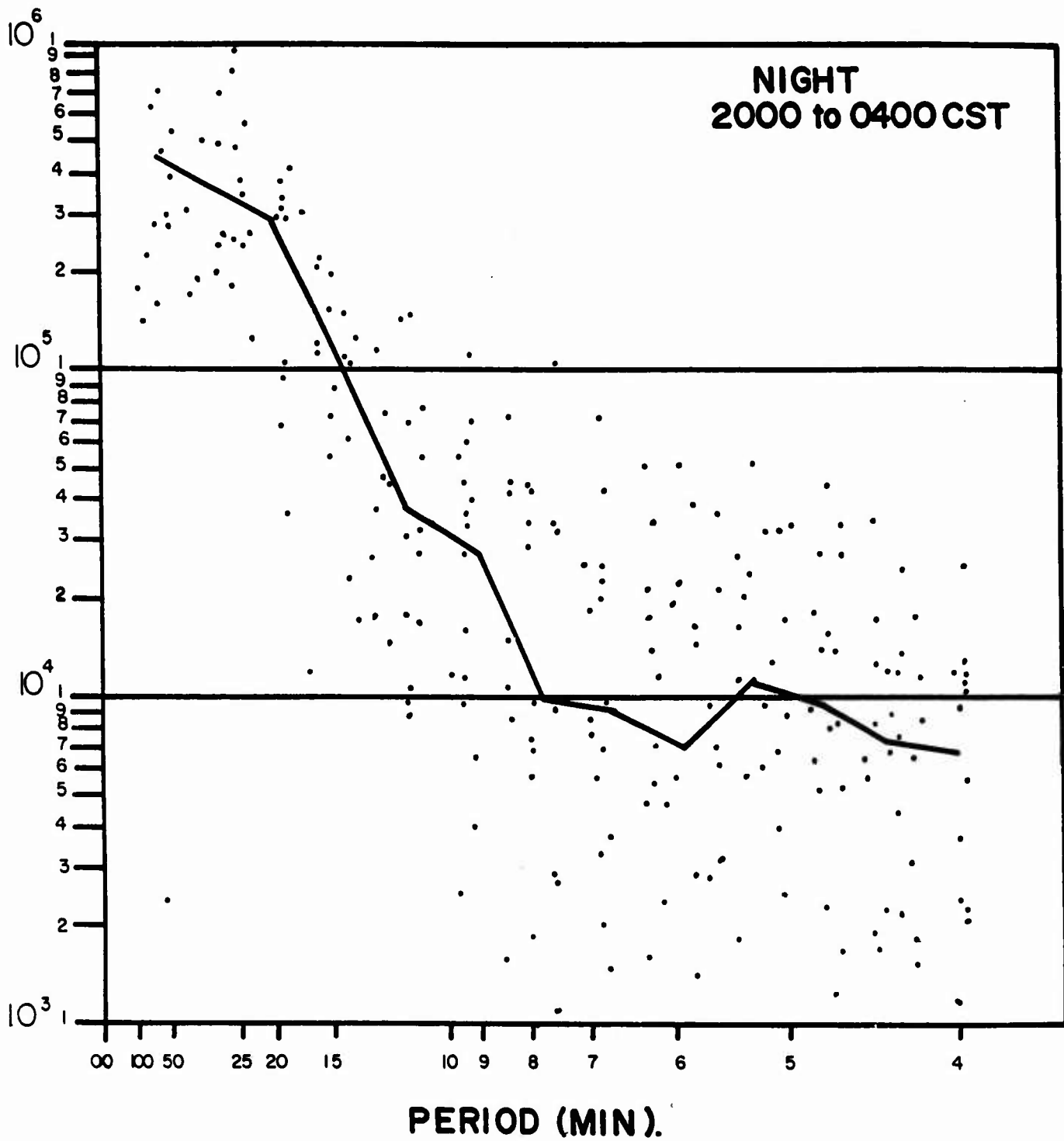Figure 8a. Median spectrum of phase variation - daytime

21

Figure 8b.   Median spectrum of phase variation - nighttime

22

of any ten-minute component in these averaged spectra and how much of this ten-minute period zone can result from one frequency spreading into an adjacent frequency. The approach to this simulation was first to use a sum of sinusoids with periods from fifty minutes down to ten minutes. The amplitude of the sine waves were adjusted to reproduce the long period part of the spectrum. The processing of these sine waves and any other components of the simulation corresponds exactly to the actual data processing. In addition to the long period sine waves, a ten-minute square wave was added, with selected amplitude and a degree of asymmetry. This asymmetry, which might reflect a different response of the ionosphere to the heating and cooling cycles, introduces a first harmonic, a five minute component, in addition to the fundamental ten-minute period. Finally many examples of the actual phase fluctuation data were examined to determine the standard deviation of the data points which would have the effect of introducing a noise component into these spectra. Several important conclusions can be drawn from this analysis. Figure 9 shows the best fit to the measured spectra.

For the daytime, in Figure 9A, a ten-minute component and shorter period components are required to produce the measured median spectrum. The required ten-minute component matches well with the long period sinusoidal components at fifteen minutes and the measured shorter period components such as at seven or eight minutes. For the daytime, it does not appear likely that the observed ten-minute component was artificially produced by the disturbing transmitter. The presence of such short period gravity waves which do not normally propagate very great distance indicates that a natural source would necessarily be located relatively close to the experimental sounder site. The noise level was set to correspond to the short period part of the spectrum (periods less than six minutes).
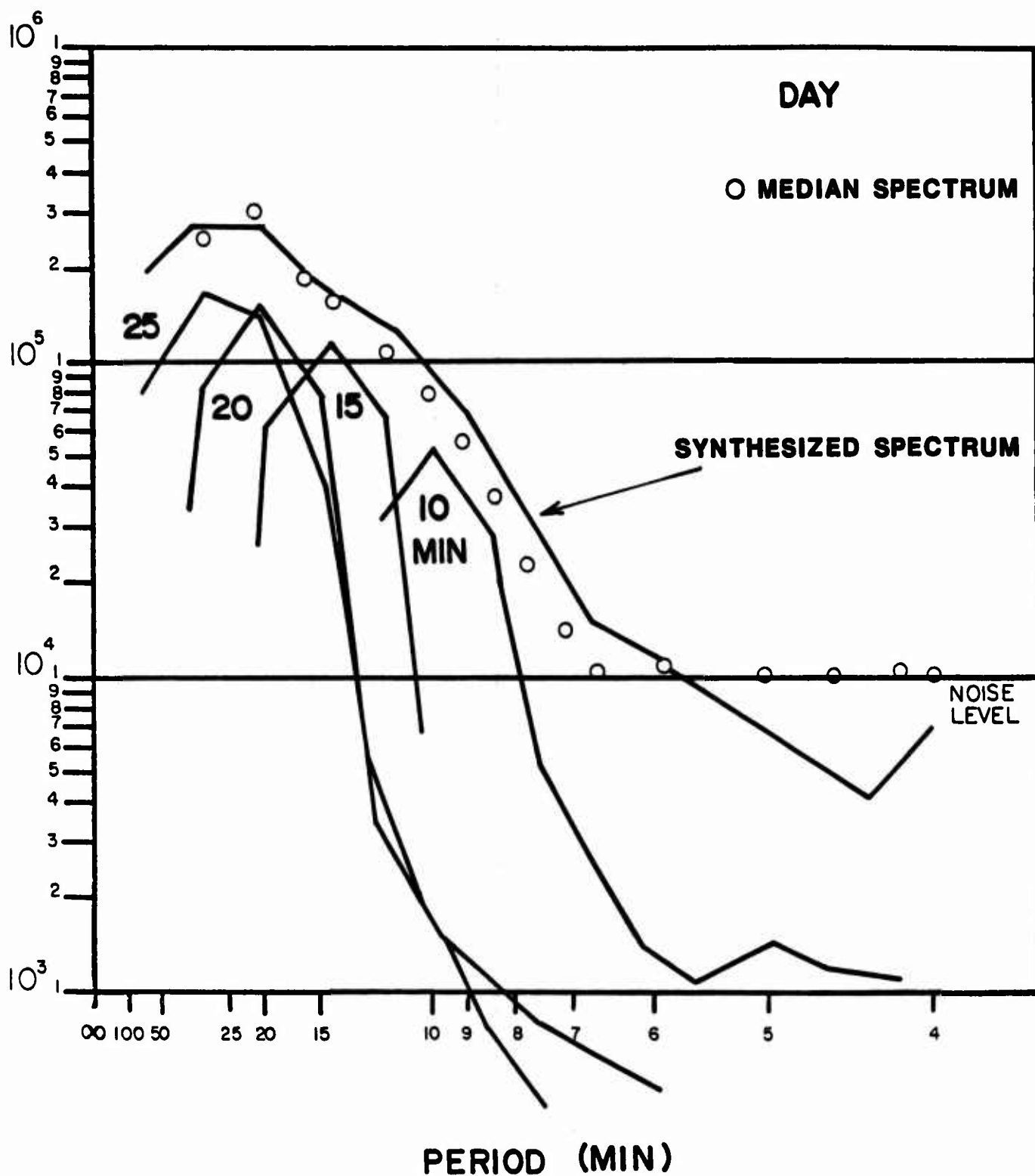
Figure 9a. Simulation of median spectrum using component
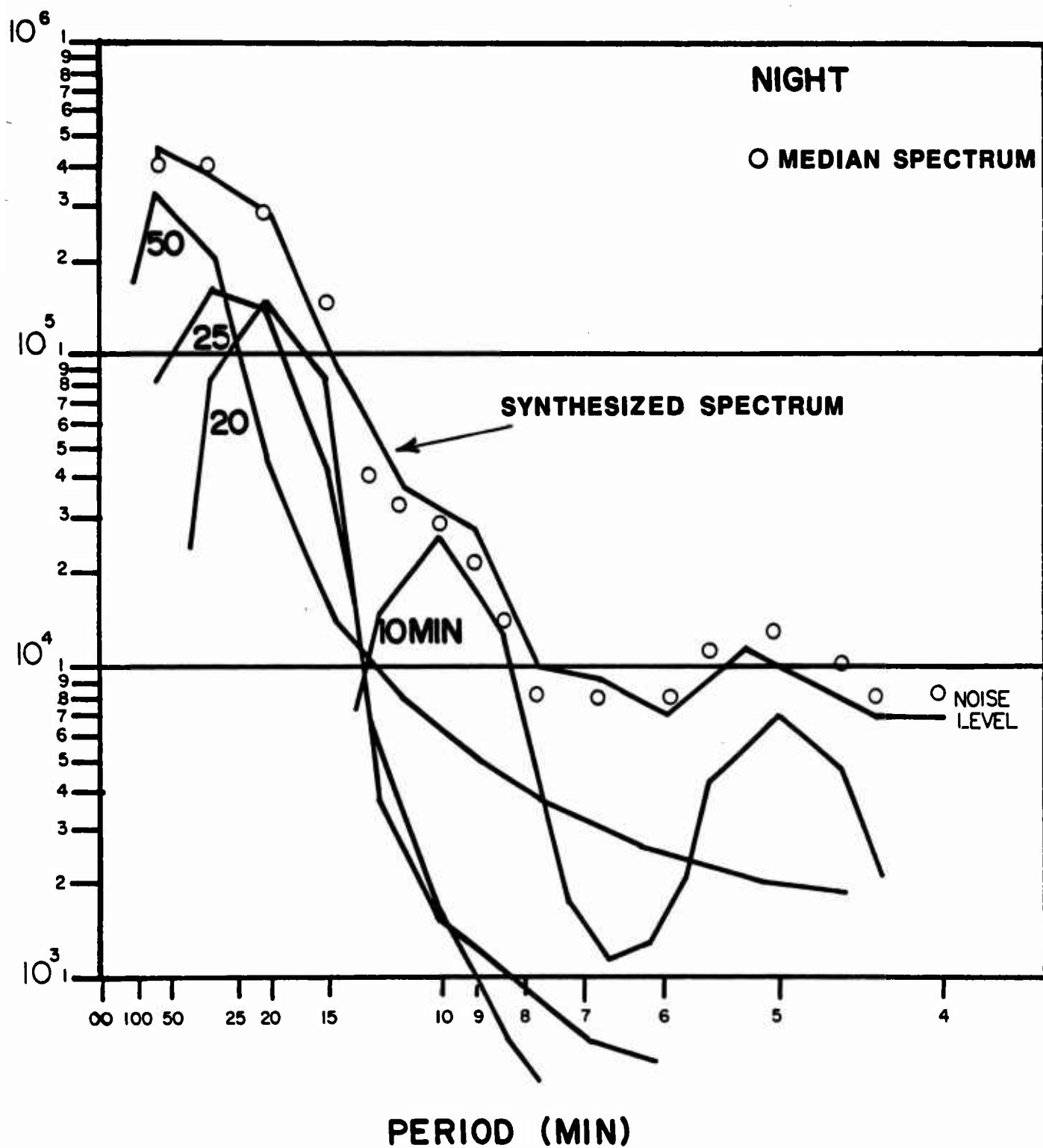waves of varying periods - daytime

24

Figure 9b.   Simulation of median spectrum using component
              waves of varying periods - nighttime

25

The situation is somewhat more clear at night (Figure 9B) where the same type of simulation was carried out. Here the dominant periods vary from twenty minutes to very long period waves of sixty minutes or greater. This analysis is limited to sixty minutes by the duration of the data samples. The detrending process would remove those periods greater than sixty minutes.

In these nighttime data, two peaks appear near ten and five minutes. The simulation indicates that these can only result from isolated frequency components at these periods and the amplitude of the peaks are not in agreement with the decay of the natural short period waves. This at least indicates a likelihood that this frequency resulted from the Ava-produced modulation. A degree of asymmetry was introduced to match the relative amplitudes of these two peaks in the nighttime data.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Considering the short duration of this experiment and the limited amount of data collected, it is not possible to draw strong conclusions concerning the ability to detect the modification of the ionosphere at a location remote from a the Ava transmitter. The observation that the spectrum of the phase fluctuations was modified during the nighttime should be very cautiously accepted at this time.

The theory, as presented by Field, indicates that the temperature change induced by the heating during the nighttime should be approximately two times greater than the daytime change given that the median disturbing frequency in day was 15.5 MHz while at night it dropped to 11.5 MHz. The observations reported here agreed qualitatively with these calculations.

The general indications are that this experiment was, at best, marginally successful and much could be gained by an improved version. Several modifications to the experiment could be made to increase the potential for success.

1. Higher P_T G_T -- somewhere between 300 kW and 500 kW with a similar or higher gain antenna system.

2. The distance to the midpoint could be reduced from 1,300 km to 900 km, as was the case in the Bochkarev experiments.

3. The heating cycle (on and off) should be shortened to approximately five or six minutes. Referring to Figure 8, on the average, the background naturally occurring phase fluctuation periods of five minutes are reduced by 3 to 8 dB relative to the ten-minute periods. This should make the detection of the modulation period easier.

4. The Digisonde's four-frequency mode should be used. Three frequencies can then sample different heights in the heated region. The fourth frequency can be set low enough so that it will be reflected from the lower part of the F-region, unaffected by the heating; it will thus provide a measure of the natural fluctuations in the ionosphere.

5. Further theoretical work must be carried out to determine the effect of transport and diffusion processes and to describe the expected behavior of the electron density in the heated region, not just the temperature variation.

6. Quantitative calculations should be performed on the propagation of radio waves through the disturbed region both at vertical and oblique incidence to determine the types of changes that are likely to be introduced by the modification process.

A conservative estimate of the improved performance of this experiment, based on changes recommended in Items 1, 2 and 3 above, is 12 dB. With this new configuration, detection of the heater modulation should be relatively straightforward.

7.0 REFERENCES

1. Bochkarev, G. S. et al., "Non-linear interaction of decameter radio waves at close frequencies in oblique propagation," JATP <u>44</u>, No. 12, pp. 1137-1141, 1982.

2. Gurevich, A. V., "Nonlinear Phenomena in the Ionosphere," Springer-Verlag, 1978.

3. Field, E. C. and C. R. Warber, "Ionospheric heating with obliquely incident waves," Geophysical Research Letters <u>12</u>, No. 11, pp. 761-763, November 1985.

4. Shoucri, M., private communication, 1986.

5. Field, E. C. and C. R. Warber, "Ionospheric modification with obliquely incident waves: Electron heating and parametric instabilities," Pacific Sierra Research Corp., PSR Report 1506, April 1985.

6. Reinisch, B. W. and Huang Xueqin, "Automatic calculation of electron density profiles from digital ionograms. 3. Processing of bottomside ionograms," Radio Science, <u>18</u>, 3, 477, June 1983.

8.0 ACKNOWLEDGEMENT

A P P E N D I X   A

Figures 5-9, 10 and 12 from PSR Report 1506, "Ionospheric Modification with Obliquely Incident Waves: Electron Heating and Parametric Instabilities," E. C. Field, Jr. and C. R. Warber, Final Report, Contract No. F19628-84-C-0014, Pacific-Sierra Research Corporation, April 1985.
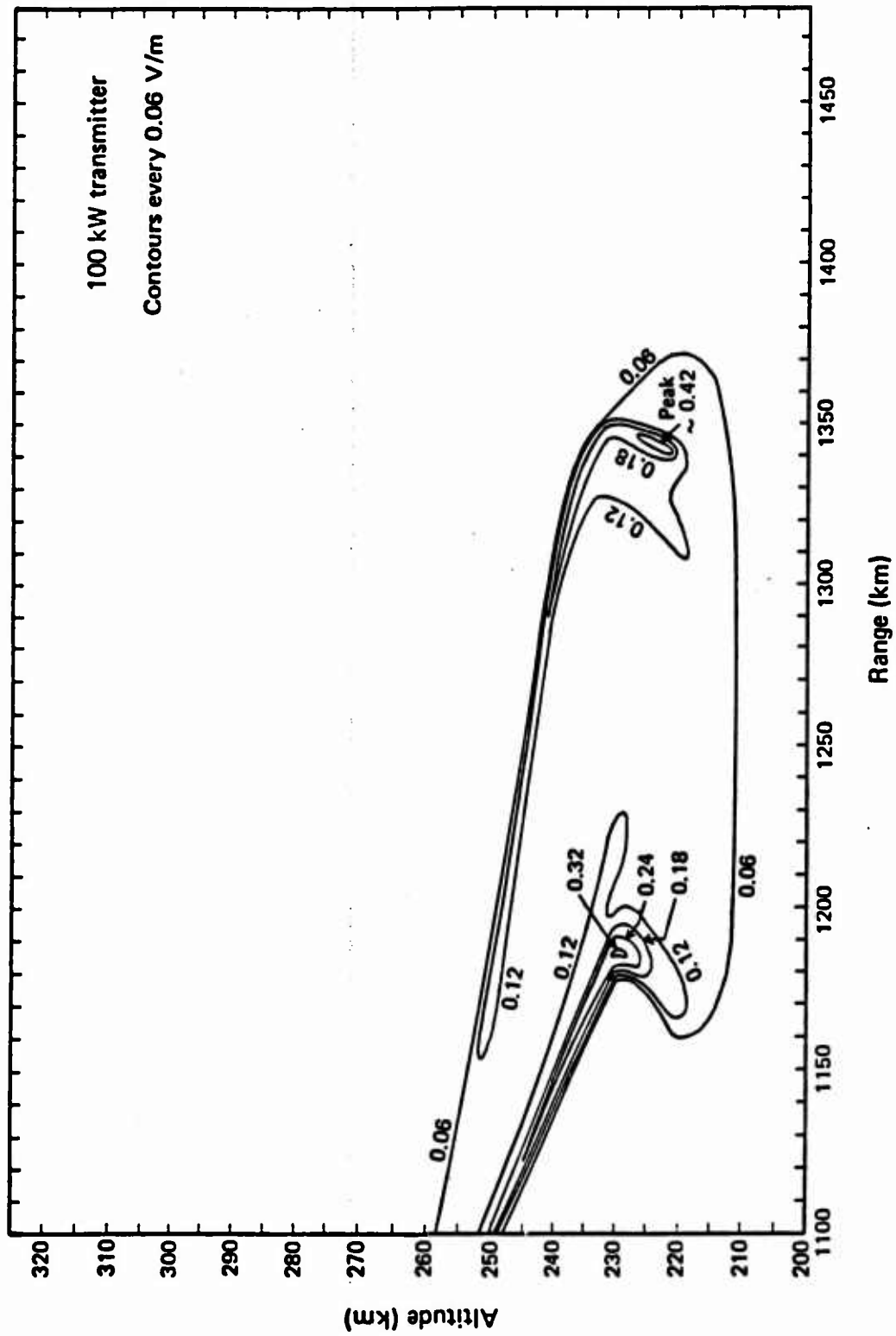
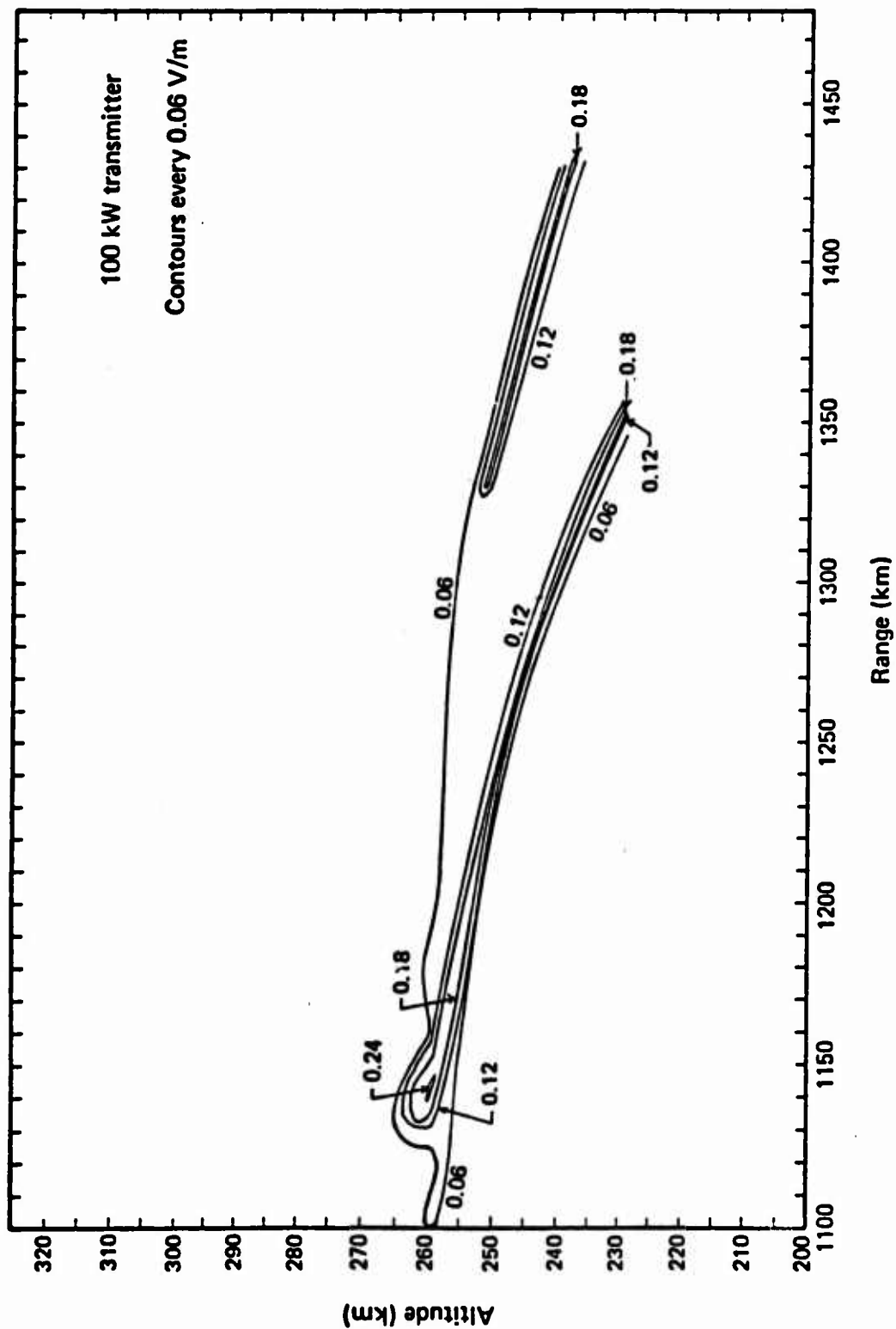Figure 5. Daytime electric field contours; frequency = 17 MHz.

32

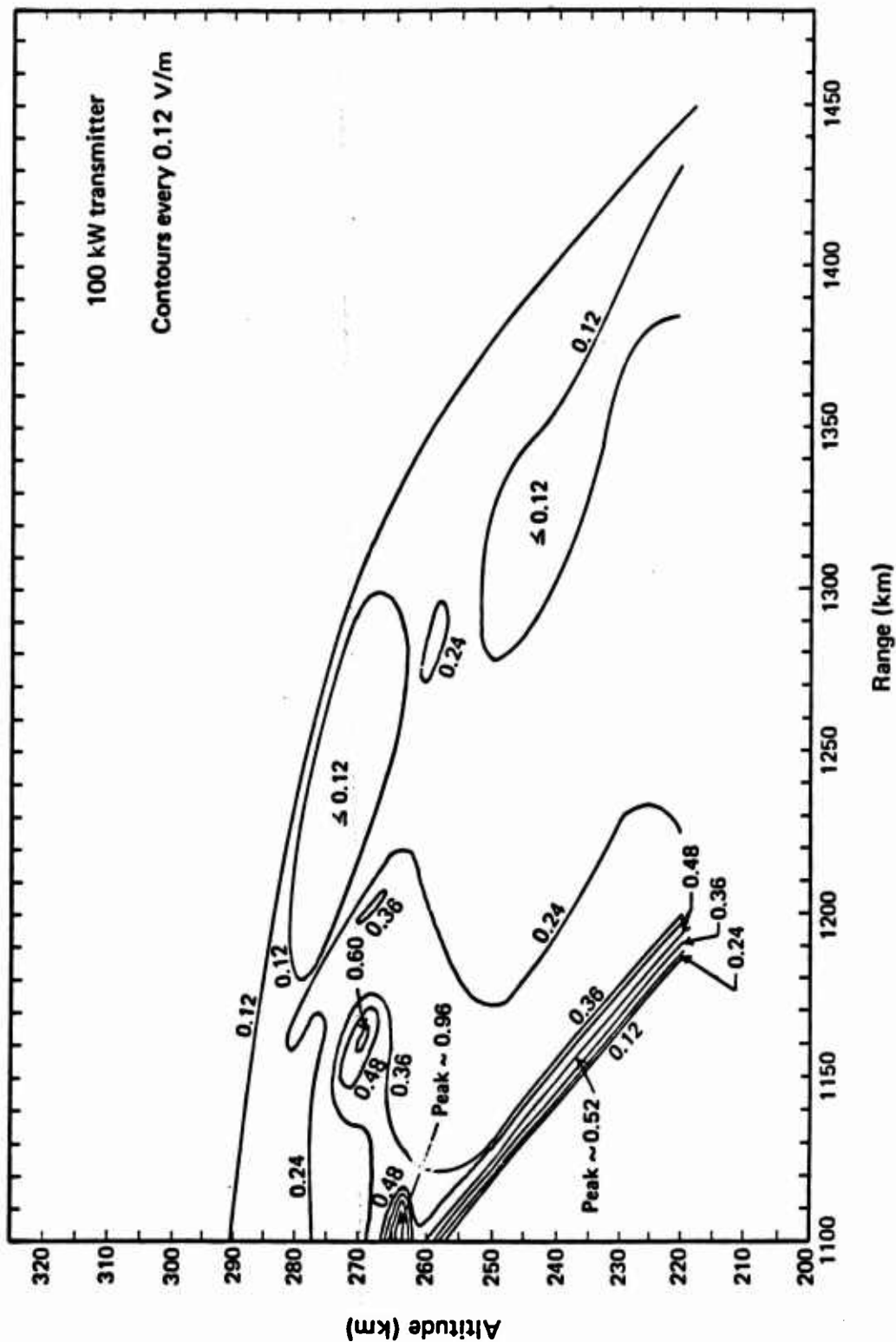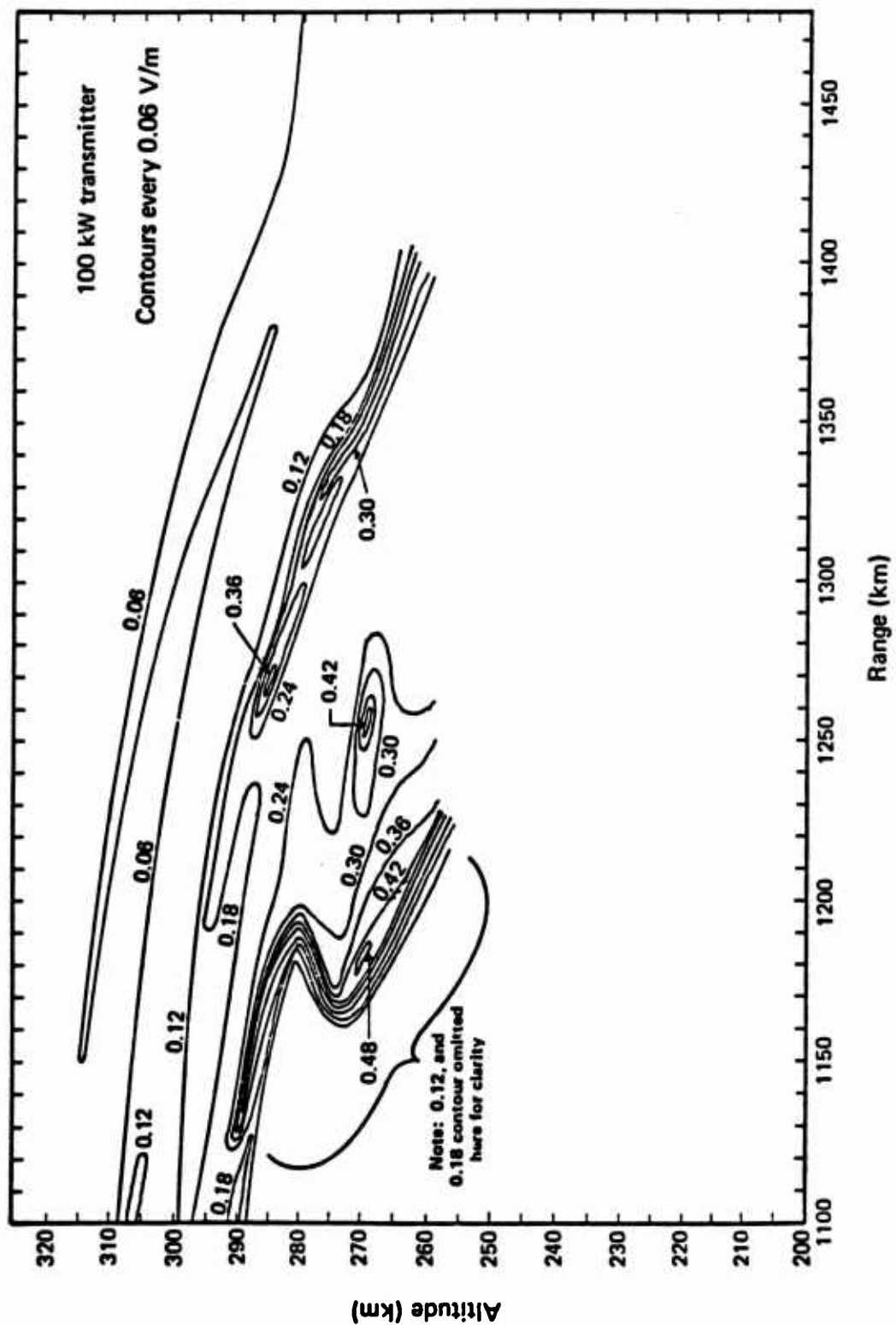Figure 6. Daytime electric field contours; frequency = 18 MHz.

33

Figure 7. Nighttime electric field contours; frequency = 8.5 MHz.

34

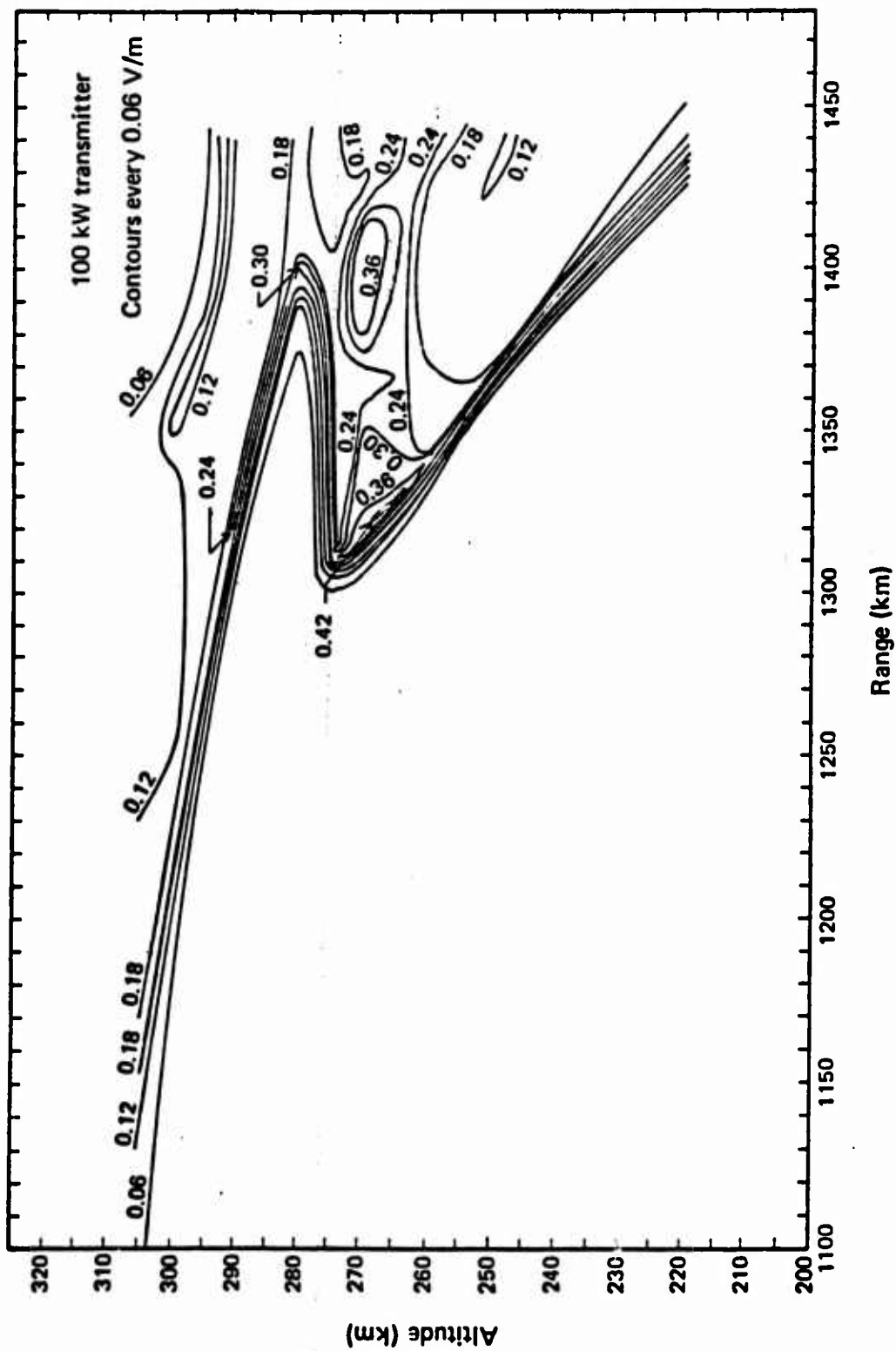Figure 8. Nighttime electric field contours; frequency = 9 MHz.

35

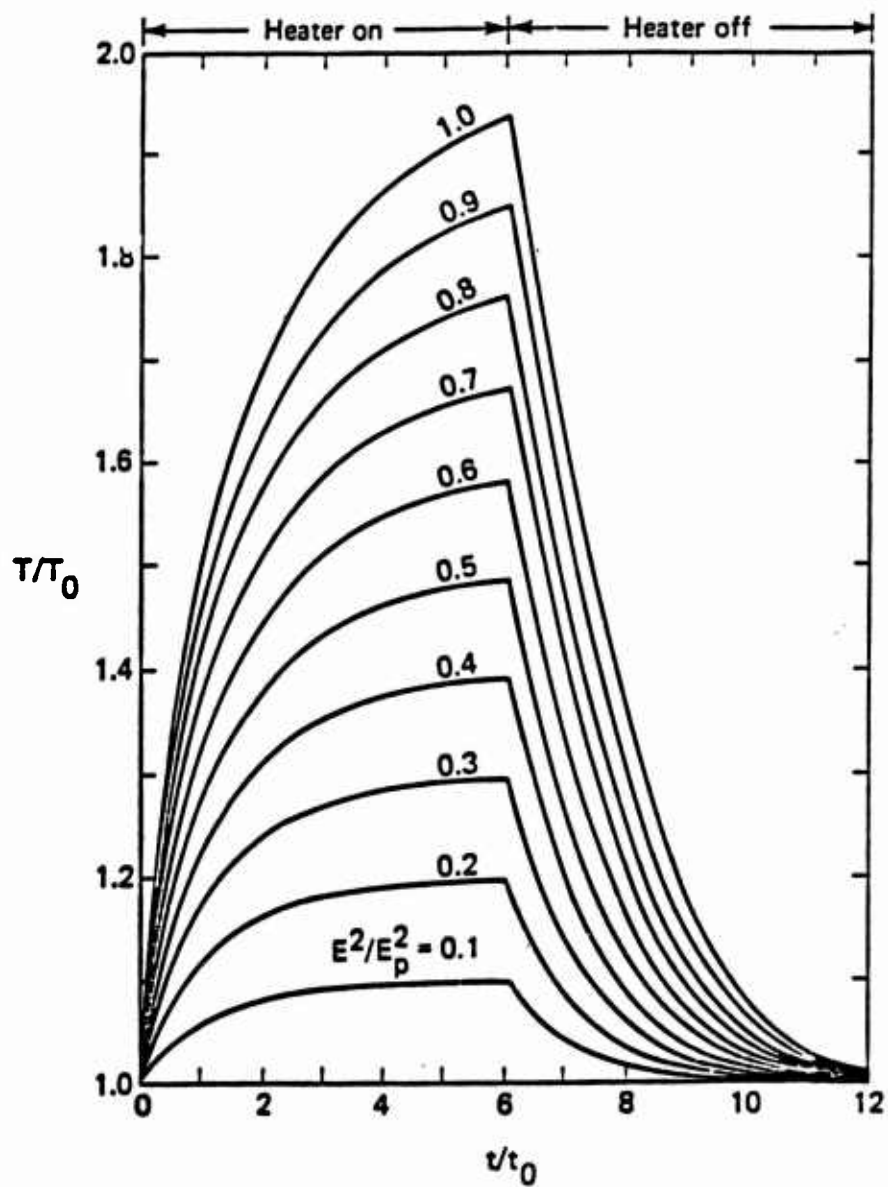Figure 9. Nighttime electric field contours; frequency = 9.5 MHz.

36

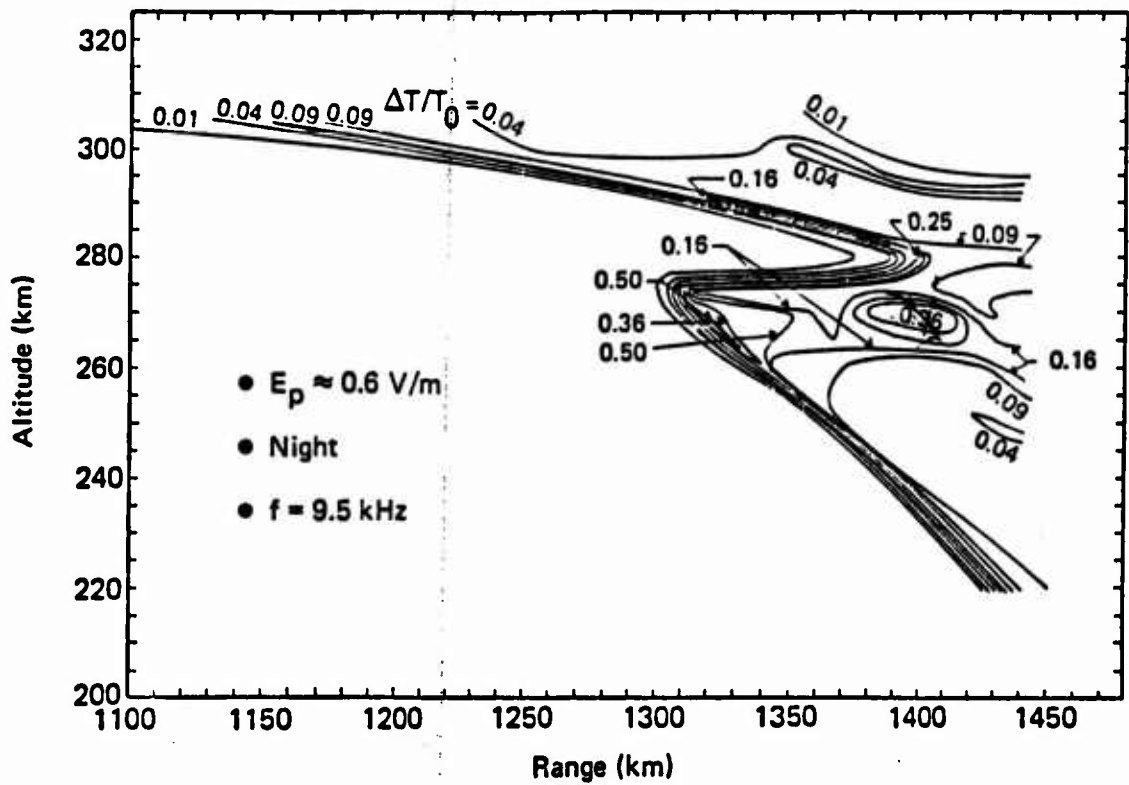Figure 10. Fractional F-layer temperature change versus time for various electric field strengths.

Figure 12. Calculated contours of electron temperature.